

Laboratory Methods of Assessing Hearing Loss

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Methods for assessing hearing loss in human and in animals are reviewed with special reference to the use of brainstem auditory evoked potentials (BSEP). The technique of recording and digital filtering of BSEP is described and compared with the results obtained by use of traditional analog filtering. The use of electrophysiological methods in assessing threshold shifts in studies of the effect of noise exposure on hearing in experimental animals is described for examples of results obtained in rats.

There are several objective methods available for assessing hearing loss. Some of these methods are suitable for use in studies of the hearing loss induced in experimental animals by noise trauma as well as in man. This presentation will discuss only the recently developed methods that make use of the evoked potentials that can be recorded from various locations in the nervous system.

The first response that can be recorded from the auditory nervous system in response to a transient sound is the compound action potential of the auditory nerve. That potential can be recorded either from the round window of the cochlea or from the auditory nerve where it leaves the ear and enters the brain through the internal auditory meatus. The other nuclei of the ascending auditory pathway also generate electrical potentials in response to a sound. Due to neural delay, these potentials appear at a later time than does the response from the auditory nerve. However, a characteristic common to all of these responses is that they can only be recorded in response to changes in sound and they are more pronounced when the sound stimulus is a transient sound than a sound of slowly varying intensity. Figure 1 shows an example of a recording of the compound action potential made from the round window of the cochlea in an anesthetized rat. The response is characterized by two peaks, the

first of which appears about 1 msec after the onset of the tone burst that was used as the stimulus. This N_1 potential is assumed to reflect the electrical activity in the auditory nerve that results from stimulating the ear with a transient sound. The second peak (N_2) appears about 1 msec later, and it is believed to originate in the first relay nucleus of the ascending auditory pathway, namely the cochlear nucleus. The amplitude of the N_1N_2 potential decreases when the sound intensity is decreased and the latency increases. These potentials exhibit a threshold, which means that below a certain stimulus intensity they can no longer be recorded.

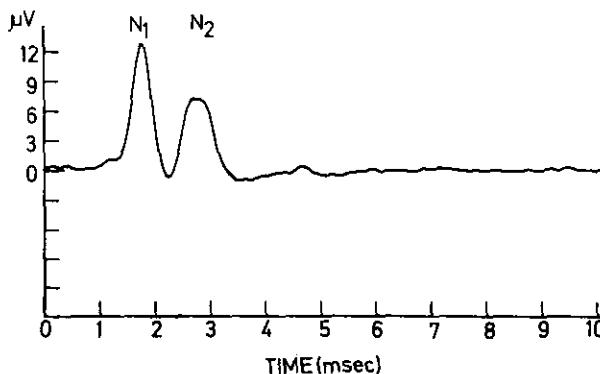


FIGURE 1. Typical compound action potential recorded from the round window of the cochlea in a rat. The stimulus was a brief click delivered to the ear via an earphone. The time scale gives the time in milliseconds after the occurrence of the click.

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When these potentials are recorded directly from the nerve or the nuclei in response to stimuli well above threshold, they have amplitudes of many microvolts and can, therefore, be directly visualized on an oscilloscope when the sound stimulus is well above the threshold of hearing.

Near threshold, the amplitude of these compound action potentials becomes smaller than that of the background noise (originating from other biological or electrical activity in the animal being tested and from the amplifiers). It therefore becomes necessary to present the same stimulus many times and average the responses to the stimuli in order to be able to identify these potentials. Such average techniques are in common use both in the laboratory and in the clinic. The averaging procedure increases the signal to noise ratio by a factor of \sqrt{N} , where N is the number of responses averaged. The responses can be averaged using specialized (usually digital) equipment or using a mini-computer.

Recordings of the compound action potentials have been used in animal experiments to study the effect of noise exposure on the ear. For this application, the sound levels, at which the compound action potentials were just discernable after averaging 500 to 1000 responses, were determined. These threshold sound levels were determined when bandpass-filtered clicks were used as stimuli. Bandpass-filtered clicks are generated by passing a short rectangular pulse (usually of a duration of 10 to 50 μ sec) through a suitable bandpass filter. The output of the filter is a damped oscillation with a frequency equal to the center frequency of the bandpass filter. The center frequency of the bandpass filter is varied over the range of frequencies where the threshold is sought. An example of such use of the threshold of the compound action potential is shown in Figure 2, which presents the thresholds of the compound action potentials in rats exposed to noise of the same energy but distributed differently over time.

These experimental results shown in Figure 2 were obtained in a study designed to test the so-called equal energy hypothesis of noise damage. This hypothesis states that it is the total noise energy to which ears are exposed that determines the degree of hearing loss. The different curves in Figure 2 show the thresholds for different stimulus intensities when the total exposure time was adjusted so that the total energy of the noise was the same. The noise was a one-octave band centered at 8 kHz. The bandpass-filtered clicks used as test sounds to determine the thresholds were generated by passing 50- μ sec rectangular pulses through a 1/3 octave filter (Bruel and Kjaer). It may be seen that the

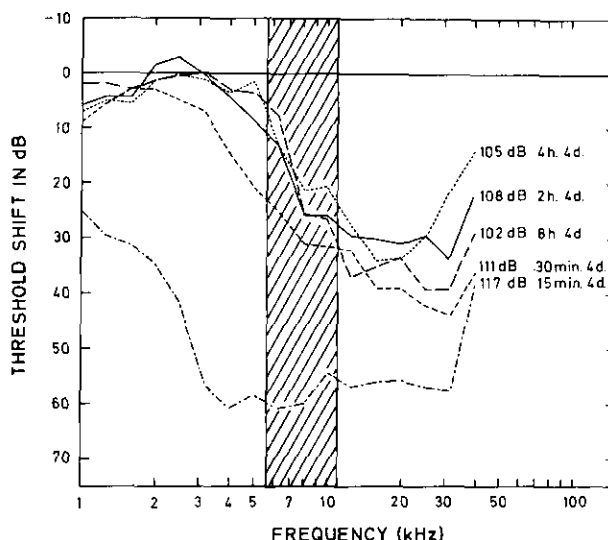


FIGURE 2. Threshold shift for the compound action potentials recorded from the round windows of rats that were exposed to noises of different intensities. The duration of the exposure was so adjusted that the total noise energy was the same. The curves represent the mean value of the results obtained in five rats for each type of noise exposure. The test stimuli were bandpass-filtered clicks (1/3 octave bandpass filters were used) and the noise used to induce the hearing damage was bandpass-filtered white noise one octave wide, centered at 8 kHz.

rats which were exposed to the lower noise intensities suffered hearing losses of about the same magnitude, thus supporting the equal energy hypothesis of noise damage. However, it is also evident that exposure for a short time to a high intensity noise is more damaging than exposure for a longer time to a less intense noise. These experiments are examples of ways in which electrophysiological methods may be used to assess the damaging effect of noise on the inner ear. These results may not be exactly identical to those obtained by behavioral evaluation of hearing loss, but they are valid for the purpose of comparison between normal (non-exposed) animals and noise-exposed animals. The electrophysiological method is frequently preferable to the behavioral method of determining hearing loss because it is much faster and the results are more readily reproducible.

Recordings from other parts of the ascending auditory pathway may also serve the purpose of determining hearing loss in experimental animals. In addition, such recordings may give other information about the effects of trauma on the auditory nervous system. For instance, it is possible to discern an effect on the ear from exposure to various chemicals.

When a recording electrode can be placed close to

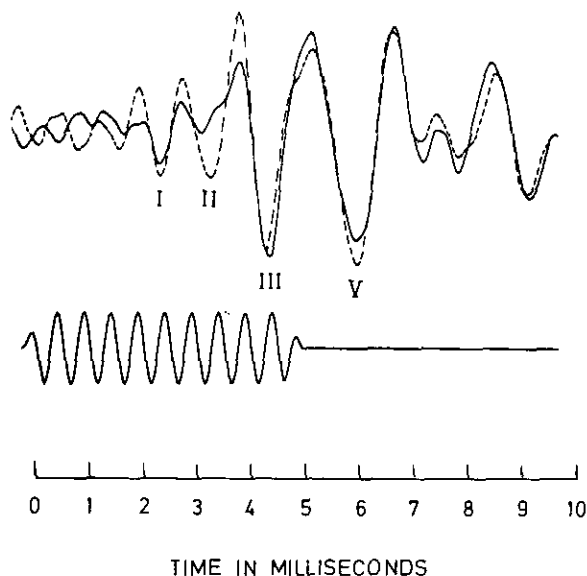


FIGURE 3. Typical response to tone bursts recorded in a human subject with normal hearing. The recording electrodes were placed on the mastoid and the forehead. The sound stimuli were 2000-Hz tone bursts, delivered to the ear from the mastoid of which the response was recorded. The tone bursts had a duration of 5 msec and were presented with an interstimulus interval of 150 msec. The hearing level of the tones was 75 dB. Two thousand responses were averaged. From Møller et al. (2).

the nerve or nucleus from which the recording is made, the potentials are relatively large and the number of responses that need to be averaged is relatively small. When recordings are done in man, the situation is usually different. Auditory evoked potentials in man can be recorded from the round window of the cochlea, but that is an invasive procedure and therefore used only in special cases. The most common method for recording auditory evoked potentials in man is to record from the scalp. Recorded in that way, the response to a transient sound such as a tone burst or a click sound is characterized by a series of peaks. During the first 10 msec after the onset of a sound, the so-called brainstem evoked potentials can be seen. When one electrode is placed on the mastoid and one on the vertex or forehead, the potentials recorded consist of a series of six to seven peaks (Fig. 3). The mastoid negative peaks are usually given Roman numerals from I to VI. Due to the large distance between the neural generators and the recording site, the amplitudes of the auditory evoked potentials recorded in that way are much smaller than those of the background noise (in this case the person's spontaneous brain activity and the noise of the amplifier, the latter being of a much

smaller amplitude than the former). It therefore becomes necessary to average a large number of responses (usually several thousand) in order to be able to identify the response. Since the ratio between the signal and the noise only increases with the square root of the number of responses averaged, the reduction of noise is a slow process when the signal is small and the background noise is large. It is, therefore, important to use other methods to reduce the background noise. One such method is spectral filtering. If some of the energy of the response is located in different frequency regions from that of the background noise, it is possible to remove some of the background noise by spectral filtering. This technique is now widely used, but unfortunately spectral filters also introduce distortion of the waveform of the recorded potentials. The filters used presently are mostly of the common analog type that attenuate either high frequency energy (lowpass filters) or low frequency energy (highpass filters). Usually both types of filtering are used and the signal is usually led through these filters before it is fed into the averager.

The distortion of the waveform that analog filters introduce by the unavoidable phase shift of such filters limits the extent to which such filters can be used to reduce noise. The availability of digital computers has made it possible to filter signals in ways that are not possible using analog filters. The design of such digital filters is much more flexible than that of analog filters since they do not need to be physically realizable (1). Figure 4 illustrates that it is possible to design a filter that does not distort the waveform of a typical evoked potential recorded from the scalp of a human subject. Particularly it may be noted that the latencies of the peaks are unchanged by filtering. These digital filters, thus, do not introduce distortion of the features that are of interest. Since it is the location of the peaks in time that is interesting, it is advantageous to enhance the peaks by using a suitable filter; this can be done easily, as seen from the recordings shown in Figure 4.

Analog high- and lowpass filters, which have about the same cutoff frequencies as the digital filters, introduce significant distortion of the recorded pattern, as can be seen from Figure 5. Of particular importance is the fact that the analog filters shift the location of the peaks in time, which the digital filters do not. Since the latencies of the peaks often are the important characteristic of these potentials, such distortion cannot be tolerated. Therefore, when analog filters are used it is necessary to select filters with a wider passband and thus, those which are less efficient in reducing the background noise.

The efficiency of the filter in enhancing the

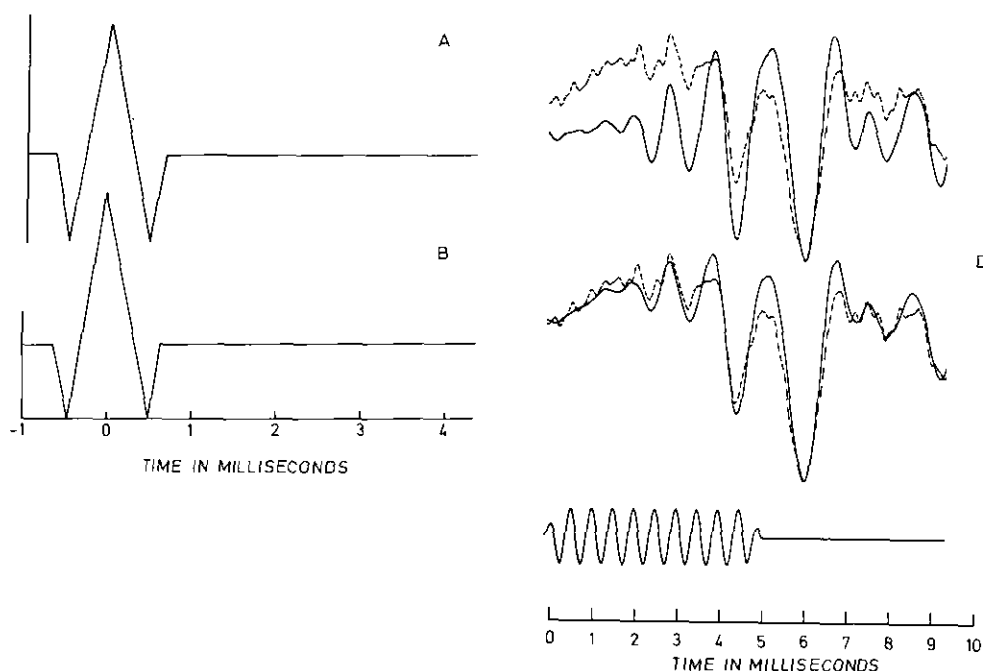


FIGURE 4. Illustration of the distortion introduced by two different digital filters (A and B) together with the weighting function of these two filters. The dashed line is the original (unfiltered) response, and the solid lines show the filtered response. The responses may be seen as representing a "clean" record of the brainstem evoked potentials since they are the average of 20,000 responses obtained in a person with normal hearing in response to 2000-Hz tone bursts presented at 75 dB above the normal threshold of hearing.

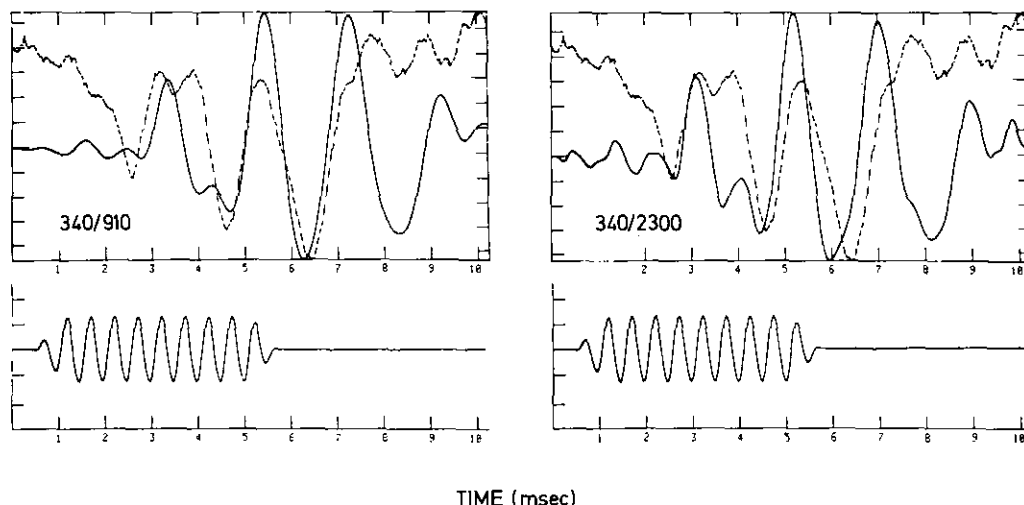


FIGURE 5. The same responses as shown in Fig. 4 but filtered by analog filters. The dashed lines are the unfiltered responses and the solid lines are the filtered responses. The filters were 18 dB/octave, minimum overshoot analog high- and lowpass filters. The cutoff frequencies were different for the two graphs and are shown by legend numbers.

response over the background noise is different for analog and digital filters. This is illustrated in Figure 6, which shows the effect of the two types of filters on the recorded scalp potentials in an individual when only a few (128) responses were

averaged. It is seen that the responses comprising the different segments of the averaged responses are more similar when digital filters are used than when analog filters are used. That indicates that the digital filters shown in Figure 3 are more

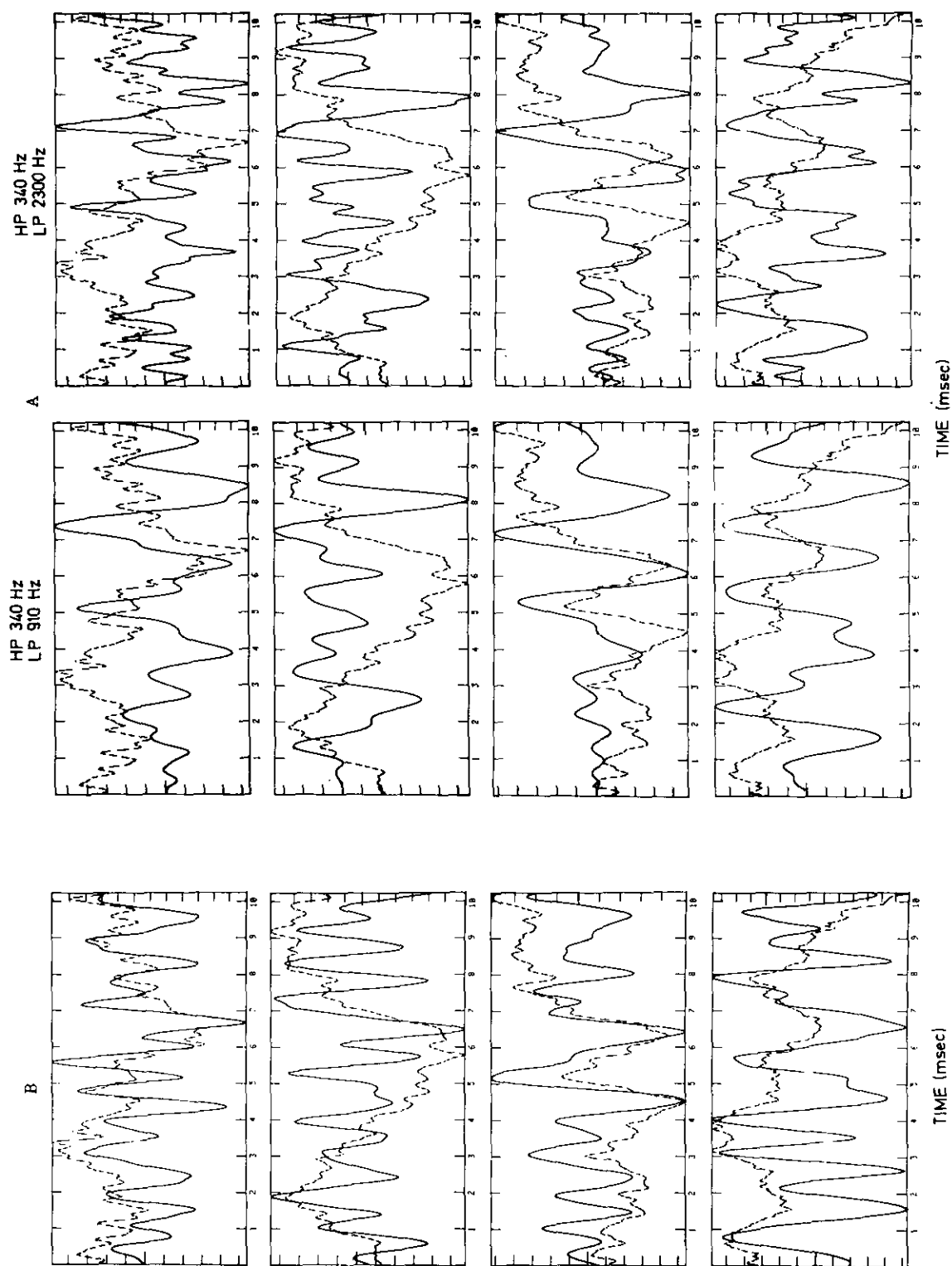


FIGURE 6. Comparison of the effects of (A) digital and (B) analog filters in enhancing the responses in the presence of background noise when only a few responses are averaged. The cutoff frequencies of the analog filters were the same as shown in Fig. 5 (and given by legend numbers) and the digital filters were those described in Fig. 4.

efficient than are analog filters in enhancing the response in the presence of background noise. The digital filter shown in Figure 3 has been in practical use in the Division of Audiology at the Eye and Ear Hospital for about two years (2).

The evoked potentials recorded from the scalp can be used in assessing the degree of hearing loss either by determining the threshold of these potentials or by comparing the sound intensity required to obtain a certain amplitude of the evoked potentials. The latencies of the various peaks in the scalp-recorded brainstem evoked potentials (BSEP) decreases with increasing stimulus intensity. This can be made use of in determining the loss of hearing sensitivity by determining the sound intensity required to obtain a response with a certain latency. In the impaired ear, a higher sound intensity is required compared to the normal ear and the difference between these two sound intensities is a measure of the loss of sensitivity of the ear. However, this method is not suitable when the damage to the ear is located in the sensory epithelium of the inner ear. In that case the so-called recruitment of loudness makes the response of an impaired ear to sound above threshold almost equal to that of an unimpaired ear. The fifth wave of the scalp-recorded BSEP (see Fig. 3) is often used to determine the hearing threshold in a person who for one reason or another cannot cooperate sufficiently to undergo ordinary pure tone audiometry. This method of recording BSEP is also suitable for

assessing the hearing loss present in experimental animals or for assessing the degree of damage to the hearing caused by noise exposure, etc. The pattern of the BSEP is different from animal to animal and between animals and man. Determination of the threshold in man is done most easily by observing the fifth peak. In animals, it may be the fourth peak that is most easy to observe to obtain the threshold. The BSEP can be recorded from the scalp in awake or anesthetized animals using surface electrodes or needle electrodes. Such measurements can be repeated in the same animal as many times as required.

When the purpose of the study is to compare the threshold in normal animals with that of animals with hearing losses, it is of no concern that the absolute value of the threshold obtained using the electrophysiological method is not exactly identical to that obtained by behavioral methods. As long as the same recording technique is used for the normal and the experimental animals, the BSEP method gives an accurate measure of hearing loss.

REFERENCES

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2. Møller, A. R., Møller, M. B., and Millner, D. A computer system for auditory evoked responses. *Proc. 14th Hawaii International Conference on System Sciences* 2: 430-438 (1981).